THE EFFECT OF CRYSTAL STRUCTURE ON MAGNETOSTRICTION

By C. W. Heaps

Abstract

Magnetostriction of steel, soft iron, and magnetite was investigated, using a Weiss electromagnet to produce the field, whose strength was varied up to 10,000 or 20,000 gauss depending on the specimen, and an apparatus of the lever type for measuring dimension changes to within about $2(10)^{-7}$cm. Curves are given showing the behavior of a steel sphere, both before and after annealing. A sphere of soft Norway iron gave larger effects than the steel sphere, effects which varied with the orientation of the sphere in the field. A soft iron disk, part of a single grain formed in a plate of iron with 3½ per cent Si, showed larger dimension changes than have yet been found in iron. *Along different diameters* of the disk quite different results were obtained; in some cases there was a contraction, in others, an expansion. Preliminary work with a magnetite sphere, 1.43 cm in diameter, indicated a lack of cubic symmetry for both the transverse and longitudinal effects. Changing the direction of the field with respect to the crystal axes may change the magnetostriction in a given direction from a contraction to an expansion; also transverse magnetostriction, with a fixed direction of magnetic field, is a contraction for some directions in the crystal, an expansion for others. *Theories* are briefly discussed. It is suggested that the ordinary magnetostriction curve of iron is the resultant of two or more different types of curves which are characteristic of the small individual crystals in different orientations, the composite curve depending on the heterogeneous arrangement of the crystals. The experiments suggest that the Villari reversal is also probably a consequence of heterogeneous crystal arrangement in the iron. Ewing's latest model of the magnetic atom seems to be capable of explaining the various magnetostrictive effects.

WHEN a bar of iron is placed with its length parallel with a continually increasing magnetic field, numerous experiments have shown that its length changes in the following way. The bar first grows longer, then contracts to its original length, and as the field increases continues to contract. In a few cases it has been found that there is no initial lengthening of the bar,[1,2] contraction resulting even in the smallest fields. It has been suggested that this failure to observe an initial lengthening is the result of insufficiently sensitive measuring apparatus. However that may be, there is no doubt but that some specimens show a much smaller initial lengthening than do others. Rhoades has found[3] that the fibrous structure of the specimen exerts a marked influence on its magnetostriction. Heat treatment is also important in determining the nature of the magnetostriction curves.

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[1] Bidwell, Proc. Roy. Soc. **55**, 228, 1894

[2] Heaps, Phys. Rev. **6**, 34, 1915

[3] Rhoades, Phys. Rev. **7**, 66, 1898

These facts seem to indicate very clearly that the crystal structure of the specimen is of considerable importance in determining the form of its magnetostriction curves and a knowledge of this crystal structure is of prime importance. A bar or wire of metal must be considered as æolotropic because it is improbable that the small crystals composing the specimen would completely retain their random orientations after the drawing or rolling process. The degree of æolotropy would depend on the mechanical treatment given the specimen so that it is not surprising that results obtained with different specimens are sometimes discordant.

The somewhat complicated behavior of iron in this respect suggests that the ordinary magnetostriction curve might be considered as the resultant of two curves, one of which would represent an expansion to a constant maximum value, the other a contraction which possibly approaches a constant value as the field increases. Suppose that when all the small crystals of the iron are oriented so as to have a certain crystallographic axis parallel with the field one of these types of curves is obtained, and when they are oriented so that all have a different axis parallel with the field the second type of curve is obtained; then for a random orientation of the crystals we should expect the resultant curve. If this view is correct, theories of magnetostriction would require considerable modification in order to explain these two curves. Actually there is no theory at present which is generally satisfactory, a fact which is not at all surprising in view of the unsettled character of our theories of ferro-magnetism.

Some experiments made on various kinds of iron and on some natural crystals of magnetite have given very different types of curves with the same specimen when magnetized in different directions. These results lend support to the hypothesis of the existence of two types of curves. It is possible, however, that the single iron crystal may give even more than these two types.

APPARATUS

For the purpose of this experiment it was necessary to measure the magnetostriction of a specimen for various orientations with respect to the magnetic field. For this reason wherever possible a sphere was the form chosen. Another advantage of this form is that an isotropic sphere is magnetized uniformly when in a uniform field, hence there are no distortions produced by the elastic transfer of stresses resulting from unequal dilatations of various parts of the same specimen. The sphere, however, has a large demagnetization factor so that a strong magnetic field is necessary in order to obtain the proper intensity of magnetization. Partly for this reason a large Weiss electromagnet with pole-pieces 10 cm in diameter and 4.65 cm apart, was used. The field, therefore, could be considered as only approximately uniform but this disadvantage seemed less than the disadvantages of using the weaker and more inaccessible field of a solenoid.

The specimens used were necessarily small. It was important, therefore, to construct a measuring device of high sensitivity. A lever system was used. In Fig. 1 (I) the sphere *G* is shown pressed by means of the spring *C* into a small depression in the brass plate *A*. The sliding crossbar pressing down on top of the spring serves to regulate this pressure. A depression in the brass plate *D* enables the sphere to be held more rigidly, and carborundum powder ground into these depressions in *A* and *D* facilitate the clamping. The brass post fixed vertically in the center of *D* passes through a hole in the plate *B* and has a glass plate fixed with sealing wax across its top. The lever *E* is made of wood, the counter-weight *F* of brass. The bearing point at *a* is a short conical glass rod with a tiny spherical tip; the bearing under *b* is an agate knife edge taken from a chemical balance, and rests on a glass bearing surface. The legs of the mirror *M* are made of small, conical glass rods with spherical tips from 0.01 to 0.02 cm in diameter, and they rest on glass plates at *c* and *d*.

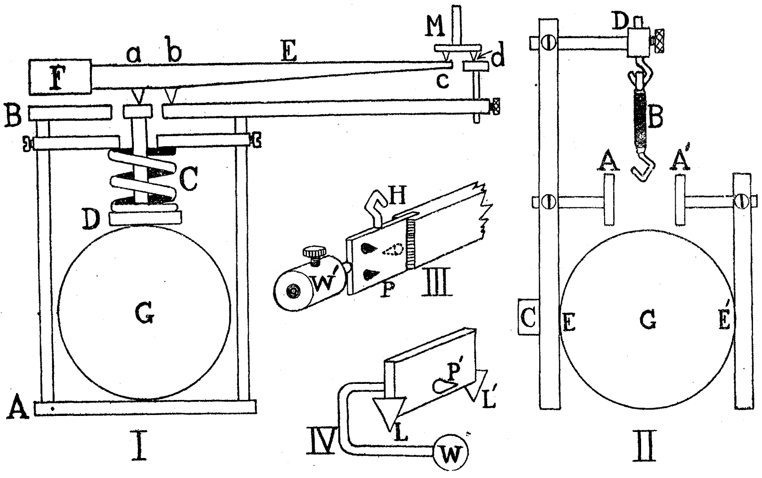

Fig. 1. Apparatus

The instrument is placed between the poles of the magnet with the lever *E* horizontal and at right angles to the field. The supporting stand, not shown in the diagram, consists of a heavy, solid brass cylinder set on end and bearing two screws between which the sphere is clamped. These screws press against opposite ends of a diameter through G perpendicular to the plane of the drawing. With this method of support it is seen that the entire apparatus for detecting dimension changes is fixed to the sphere itself, so that any small motion of the sphere as a whole will not introduce large errors.

No iron is used anywhere in the measuring device. The dimensions of the lever system were as follows: $ab = 0.31$ cm, $bc = 31.7$ cm, $cd = 0.184$ cm. The image of a lamp filament was reflected from M upon a scale which during most of the experiments was 365 cm distant. The magnifying power is therefore calculated to be 405,700.

The instrument shown in Fig. 1 (I) is capable of making measurements only of dimension changes perpendicular to the field. To measure the longitudinal effect, that is, the dimension changes parallel to the field, the apparatus shown in Fig. 1 (II), (III) and (IV) was constructed. Referring to (II), two vertical wooden bars were fixed to the ball at E and E', either by the use of de Khotinsky cement or by means of small brass screws threaded into the ball. A and A' are two glass plates, the distance apart of which may be easily altered. B is a rubber cord supplied with hooks as shown. At C is fixed a long wooden arm extending out perpendicular to the plane of the drawing and carrying at its end a small adjustable glass platform like that shown in (I) under d. The weight of this arm was counterbalanced by an extension backward to the other side of C. In (III) is shown a section of the lever used here. A hook H and a counterweight W' are fixed to the glass plate P. Glass bearing points are fixed with sealing wax to this plate as shown, one of the points being supposed visible through the plate. These bearing points were made as short as possible in order to secure greater strength. The spherical tips were from 0.01 to 0.02 cm in diameter. This lever was hung by the hook H to the bottom end of the rubber cord B, the plates A and A' were adjusted against the glass bearing points, and the rod D turned about a vertical axis till the pressure of the bearing points against the glass plates was sufficient to hold the lever in a very stable position. The end of the lever not shown in the diagram carried a small glass plate with its plane vertical. This plate was designed to press against the glass bearing point P' fixed to the mirror of diagram (IV). The legs L and L' of this mirror were triangular pieces of glass chipped from a thin cover glass. The points were very sharp. The counterweight W was sealing wax stuck to the bent glass rod as shown. This mirror stood on the glass plate at the end of the arm C, the line LL' being parallel to the length of the arm. The weight W was adjusted so that the mirror was in equilibrium on its two legs but leaned forward quite appreciably. The plate on the end of the lever shown in (III) by pressing against the point P' held the mirror so that its plane was approximately vertical. Any motion of the end of the lever arm would thus alter the tilt of the mirror. To prevent slipping the surface of the glass platform carrying the mirror was ground with fine carborundum; in fact it was found advantageous to grind in this way all of the glass plates used in the apparatus as bearing surfaces. The sphere under test was supported between screws at G just as in the first apparatus, but the support was turned so that the magnetic field was parallel to the line joining EE'. The magnifying power of this system was about the same as that of the one shown in (I).

The magnetic induction through the specimen was measured by means of a carefully calibrated fluxmeter connected to several turns of wire wrapped around the sphere. The sphere was placed between the poles of the magnet and the fluxmeter deflections noted when the exciting current was turned on or off. The effect of the residual field of the magnet was thus neglected. It amounted to about 35 gauss.

Sources of Error

One of the chief sources of error lay in the non-uniformity of the magnetic field. When an iron sphere was placed between the poles of the magnet quite a strong force acted upon it unless it was very carefully centered between the two pole-pieces. This force was always made as small as possible by careful adjustment but it was probably always present in some degree. This force on the ball was resisted by the pressure of the screws supporting the ball, hence distortions of a nature not desired in this experiment would arise. However, it was concluded that such distortions were small compared with other magnetostrictive effects for the following reason. When the sphere was properly centered no motion of the ball or its support could be detected when the magnet was excited, though of course the mirror was slightly tilted by the magnetostriction of the ball. With the exciting current off pressure was applied to one side of the ball till a slight motion of the support could be detected. The spot of light reflected from the mirror vibrated violently under these conditions but its rest position appeared to be unchanged. The resulting dimension change must, therefore, have been too small to shift the zero position of the mirror.

Another source of error might lie in the magnetic traction on various light movable parts of the apparatus. No iron was used in the construction but it seems possible that some effect of this kind was present.

When a ring of brass was substituted for the ferromagnetic sphere the largest magnetic field used produced a deflection of the spot of light of about 1 mm. The cause of this deflection might have been a contraction of the brass ring, a tilting of the support due to some slight motion of the base of the magnet, or a direct action of the non-uniform field on the lever system. This error was not eliminated. In most cases it was small compared with the observed deflection.

The pressure of the screws holding the specimen could not be adjusted to have always the same value, hence in general there would not be the same magnetostriction effect after a readjustment of the specimen because the magnitude of magnetostriction depends on the state of strain of the specimen. This source of error is probably too small to be important.

Temperature changes of the specimen caused a slow drift of the spot of light. However it was not difficult to separate this temperature effect from the magnetostrictive effect. Readings were taken rapidly to minimize this error. There was always an irregular motion of the spot of light, sometimes amounting to a slight blurring of the image, because of vibrations of the building. By choosing quiet hours of the day these vibrations were made small enough to cause little trouble.

When cement was used at E and E', Fig. 1 (II), there frequently existed a steady and fairly rapid drift of the zero point on the scale. This was caused by a viscous yielding of the cement. In only one instance was a satisfactory curve obtained under these conditions. Where possible brass screws were used to fix the supports to the ball; in the case of magnetite the sphere was fitted into depressions in the supports and the supports held firmly by rubber bands passing around the ball and the two supports. Carborundum powder at E and E' prevented slipping.

The apparatus gave reproducible results, a condition which has not always been realizable with this type of apparatus.[4] The bearing points L and L' did not slip on the ground glass surface. Such a slipping would have been indicated by a characteristic displacement of the zero after any motion of the mirror.

RESULTS

The first experiments were made on a steel ball of diameter 1.9 cm, and only the dimension change perpendicular to the magnetic field was measured for this specimen. Fig. 2 shows the curves obtained with this ball before and after annealing. The change of diameter per cm (dL/L) is plotted against the magnetic induction B. The diameter

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[4] Rhoades, Phil. Mag. **2**, 468, 1901.

transverse to the field is seen to decrease for the fields used and annealing has increased this contraction effect. The arrows beside the curves indicate whether the field was increasing or decreasing when the respective curves were obtained. Hysteresis is peculiar in that the ball continues to contract as the field is decreased from the maximum value till its diameter is smaller than anything obtained with the increasing field. These results are in qualitative agreement with most of the work of previous experimenters. Bidwell, it is true, has found annealing to decrease the magnitude of the effect in one specimen but this result seems to be an exception to the general rule. Nagaoka[5] and others have found the return curve of the hysteresis loop crossing the initial curve. Possibly insensitiveness of the apparatus has prevented this phenomenon from showing in the curves of Fig. 2. Rhoades, however, did not observe this crossing in most of his specimens. Self-demagnetization of the sphere was so great that the sphere returned approximately to its original dimensions when the magnetizing current was cut off. By using the fluxmeter it was found that the intensity of magnetization remaining in the annealed sphere after a cycle had been performed was less than 15 units.

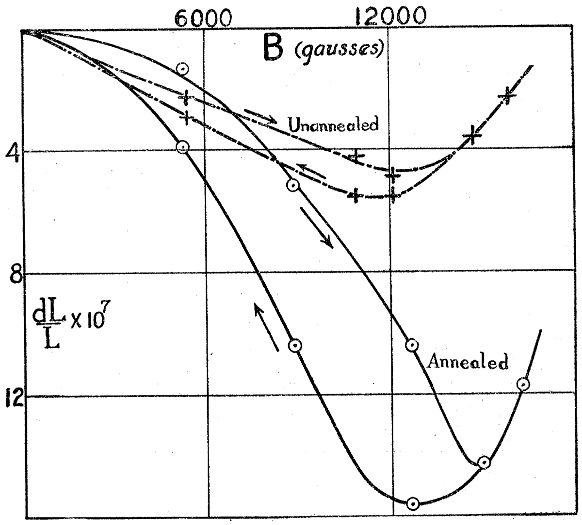

Fig. 2. Magnetostriction for steel ball, perpendicular to the field

The next sphere examined was turned from a cylindrical bar of soft Swedish iron. Its diameter was 1.46 cm. Curves *A* and *B*, Fig. 3, show how the transverse contraction of the sphere varies with the induction through the sphere. For curve *B* the contraction was measured

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[5] Nagaoka, Phil. Mag. **37**, 131, 1894

along the axis of the ball (the axis being defined as the direction parallel with the axis of the original bar from which the ball was turned), the magnetic field being perpendicular to this direction. For *A* the field was parallel to the axis, the contraction perpendicular to this direction. The circles near curve *A* are observations made when both the contraction and the magnetic field were perpendicular to the axis. Curves *C* and *D* represent expansions in the direction of the field. For *C* the axis of the ball was parallel with the field, for *D* it was perpendicular to the field.

These curves show that the maximum longitudinal expansions and transverse contractions are of the same order of magnitude. It is of interest to note that according to these curves the volume of the sphere is first diminished then increased as the induction increases. Calculation shows that the longitudinal elongation must exceed twice the transverse contraction before the volume of the sphere is increased by the magnetization, and this condition is not realized till the induction is around 17,000. Nagaoka and Honda[6] have found the volume of an iron ovoid to increase continually in a longitudinal field. Bidwell observed the dimension changes of an iron ring and concluded that the volume of the ring was decreased by magnetization. These con-

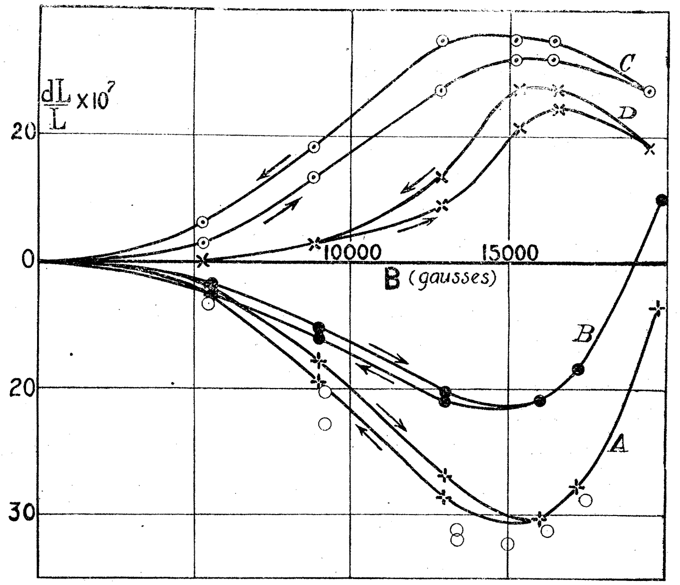

Fig. 3. Results for soft Swedish iron.
A and B transverse effect; C and D longitudinal effect

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[6] Nagaoka and Houda, Phil. Mag. **46,** 261, 1898

tradictory results may be explained by differences in the nature of the iron used.

The curves of Fig. 3 corroborate the work of Rhoades and others in demonstrating the effect of fibrous structure on the magnetostriction curve of iron. It seems probable, however, that the mechanical treatment of the bar during its fabrication has not succeeded in producing any very great lining up of the elementary crystals of the iron; the magnetostriction curves for different orientations of the sphere are too similar. Furthermore, the induction in the specimen seemed to be independent of its orientation in the field.

A crystal of magnetite, an octahedron, was next ground into a sphere of diameter 1.43 cm. This sphere had a few pits in it but on the whole was satisfactory. Though belonging to the cubic system this crystal showed a tendency to split along a certain direction. In other words, there was one plane perpendicular to one of the four trigonal symmetry axes of the crystal which favored cleavage more than any other. When placed in the magnetic field the induction in this sphere, measured as described above, was found to be independent of the orientation of the sphere. A more sensitive apparatus might have detected differences, for Quittner[7] has investigated magnetite and found the magnetic properties varying in a complicated way for different directions and different field strengths. The magnetostriction of this sphere was studied for a number of different positions of the crystal. Curves similar to those of Fig. 4 were obtained, and the orientation of the crystal was found to be an important factor in determining the form of the curve. Hysteresis effects were smaller than in the case of iron so are not shown in the curves, which give results for an increasing field. For some positions of the sphere curves were obtained which were not like those of Fig. 4, but they could have been produced by a combination of the types there shown. The two continuous curves of Fig. 4 represent the magnetostriction transverse to the field for two different settings. These particular curves are reproduced because they show respectively the maximum contraction and maximum elongation observed in directions perpendicular to the field. The contraction curve (plotted below the B axis) was obtained with the field making an angle of 45° with that crystal axis which is perpendicular to the plane of easy cleavage. It is not known whether the field in this case was parallel to a tetragonal axis, though such might have been the case. The contraction was measured normal to the plane determined by the magnetic field and the

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[7] Quittner, Ann. der Phys. **30**, 289, 1909

above-mentioned trigonal axis which is perpendicular to the plane of easy cleavage.

The expansion curve (the continuous line plotted above the *B* axis) was obtained when the sphere was arranged just as above except that the magnetic field had been turned through 90° about the diameter of the magnetite sphere. Simply changing the direction of the magnetic field with respect to the crystal axes has sufficed, therefore, to convert its effect along a given perpendicular direction from a contraction to an expansion.

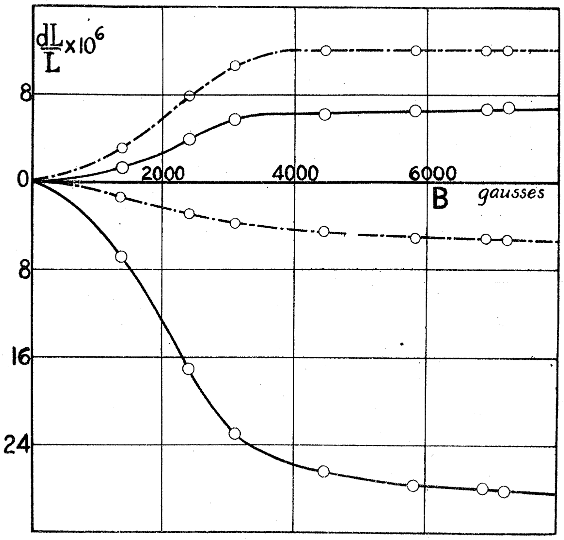

Fig. 4. Curves for various positions of a spherical magnetite crystal

If the direction of the magnetic field is kept constant and the sphere rotated about this direction as an axis the magnetostriction in different directions perpendicular to the field may be observed. In this case an angular displacement of 90° was found to convert a contraction into an expansion.

The dotted curves of Fig. 4 represent magnetostriction in the direction of the magnetic field. The expansion curve, above the B axis, was obtained along a trigonal symmetry axis; the contraction curve, below the B axis, was obtained with the field in one of the principal planes of symmetry of the crystal.

These curves for magnetite show the vital importance of crystal structure in relation to magnetostriction. A more detailed investigation of the relation of the crystalline axes to the dimension changes is desirable, expecially in view of the fact that magnetite does not obey the laws of cubic symmetry in its magnetic behavior. With the apparatus here used there was not sufficient ease or accuracy of adjustment. Furthermore the locating of these axes in the sphere was difficult, their directions having been lost during the grinding process. The specimen did not appear to have cubic symmetry as regards magnetostriction, however.

The magnetic properties of crystalline iron have been studied by Beck and a summary of his work is given by Kunz.[8] The symmetry required by the cubical system is apparently not rigorously satisfied by the magnetic properties of iron crystals but the deviations are much smaller than in the case of magnetite. The writer has been unable to secure iron crystals large enough to make a sphere of the proper size for investigating magnetostriction. However, some plates of silicon iron alloy (about $3\frac{1}{2}$ per cent Si) were available, in which the grains were of large size.

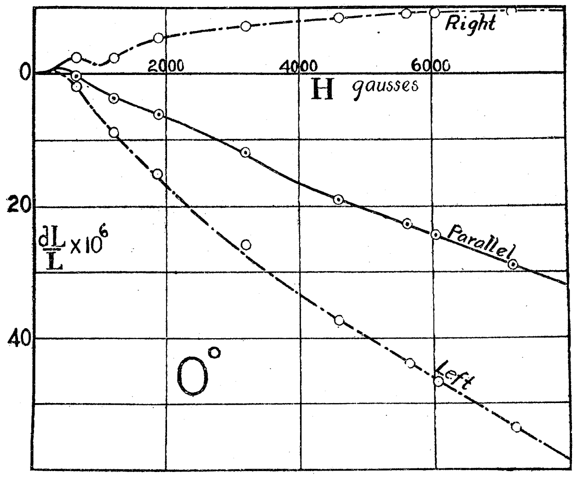

Fig. 5. Iron disk; plane parallel to H, and slightly to the right and to the left, as marked

A single grain was cut from one of these plates and turned into a flat disk 1.7 cm in diameter and 0.07 cm thick. The magnetostriction apparatus for the longitudinal effect was then fixed to the edges of this plate and the disk supported vertically between the flat ends of two brass screws which pressed from opposite sides against the center of the disk. To make the mounting secure it was necessary to wedge the edges of the disk tightly into the slots in the heads of brass screws. These screw heads were then fitted tightly into holes on the magnetostriction ap-

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[8] Kunz, Bull. Nat. Res. Council, 3, 165, 1922

paratus. Rubber bands wound around the outside of the attached uprights increased the rigidity of connection.

In Figs. 5, 6, 7, and 8 are shown the results obtained with this iron disk in a longitudinal field. The relative change of length of a diameter of the disk is here plotted against the field strength H (measured in the absence of the disk) instead of against the magnetic induction. In connection with these curves it is to be remembered that the plane of the disk is vertical and at the same time parallel with the magnetic field. It very soon became apparent that slight errors in adjusting this plane parallel to H resulted in decidedly large modifications of the magnetostriction curves. For this reason three curves were obtained for each diameter of the disk which was investigated. The first curve was secured when the plane was to all appearances parallel with H. Two other

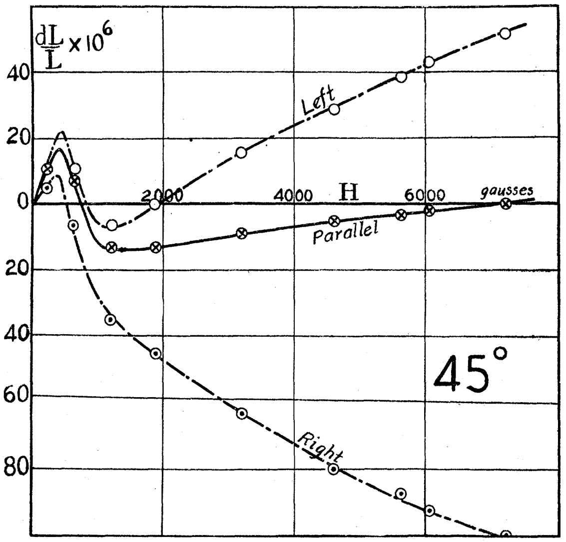

Fig. 6. Same as Fig. 5 but along a diameter at angle of 45° to the first

curves were then secured when the plane was turned successively through a small angle to the right and to the left of the parallel position. The three curves of Fig. 5 marked 0° were the first obtained in this way, the positions of the disk being indicated for each curve. The disk was then removed and replaced so that magnetostriction along a diameter 45° from the first could be observed. This set of three curves (Fig. 6) is marked 45°. In the same way the magnetostriction along diameters 90° and 135° from the first was measured and results plotted in Figs. 7 and 8.

The magnitude of the dimension changes is larger than has been previously found and in most cases the curves are not like those for ordinary iron. Hysteresis effects are not shown in the diagram, all the curves having been obtained with an increasing field. For some positions hysteresis was quite important; in one case the diameter of the disk expanded quickly to a certain point as soon as the field was produced and then continued to expand slowly for some time in this constant field. The intensity of magnetization of iron has been found to exhibit a similar viscous yielding.[9]

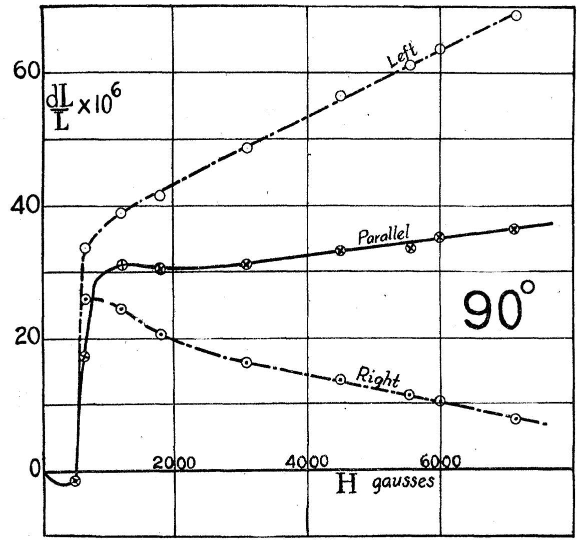

Fig. 7. Same as Fig. 5 but along a diameter perpendicular to the first

A possible source of error must be considered in connection with these curves. If the disk is not accurately parallel with the magnetic field a torque will be set up tending to twist the plane into line with the field. This torque will be opposed by the two screws between which the plate is clamped and the result will be a distortion of the disk which is not a true magnetostrictive effect. It appears from the curves that this error is not very large, for when the disk is turned to the right of the parallel position one would expect the error due to this torque to be in the same direction as when the plate is turned to the left of the parallel position. Except for very small fields the curves show that such is not the case. We may conclude, therefore, that these curves give a fairly accurate representation of the true magnetostriction effect, at least for large enough values of the field.

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[9] Ewing, "Magnetic Induction in Iron," p. 127. A. M. Mayer (Phil. Mag. **46**, 177, 1873) has measured the time required for magnetic expansion to take place.

Making this assumption we may draw the following conclusions. The character of the longitudinal magnetostrictive effect may be completely changed by changing the direction of the magnetic field with respect to the crystal axes of the specimen; a contraction may be converted into an expansion. The complicated nature of these curves suggests that the field was never parallel to a principal axis of the crystal. The large effect produced by turning the plane of the disk slightly out of the direction of the field, especially for the 135° position, and the nature of the curves secured in this displaced position might indicate that a principal axis of the crystal does not lie in the plane of the disk. Such a conclusion might be reached by assuming that simple types of curves are obtained along the axes and more complicated combinations for other directions. It is possible, of course, that the grain does not possess a perfect crystalline structure, in which case little can be conjectured regarding the location of axes. A second grain, turned into a disk 1.48 cm in diameter, gave results similar to those described.

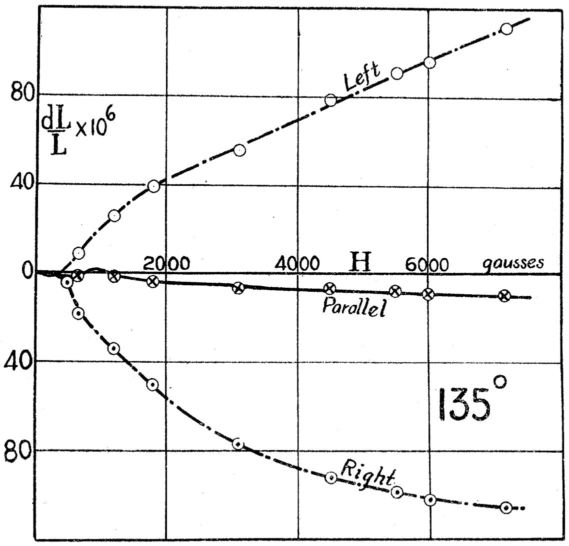

Fig. 8. Same as Fig. 5 but along a diameter at angle of 135° to the first

Discussion of Results with Reference to Theories

These investigations show conclusively the importance of crystal structure in relation to magnetostriction. The type of curve usually obtained with rings and bars is like the dotted curve marked "right" on the 45° diagram of Fig. 6, and attempts have been made to explain this curve on the basis of certain assumptions regarding molecular structure. It now appears that a number of curves of different types will have to be explained. Before a correct model of the magnetic atom in iron can be constructed it will be necessary to investigate carefully the magnetostriction curves in relation to the axes of the iron crystal, for it appears that the effect is determined very largely by the direction of the magnetic field with respect to these axes.

Perhaps the most satisfactory type of model is the one recently proposed by Sir J. A. Ewing.[10] This model of the magnetic molecule consists of an outer fixed shell of magnetic elements and an inner movable magnetic mechanism resembling the original Weber element. The forces between the fixed outer shell and the inner element are supposed to determine the degree of stability of this inner element, and according to Ewing these forces may be capable of producing a distortion of the molecule. It is the outer shell which determines the ordinary mechanical or crystalline properties of the solid. A distortion of the outer shell could thus easily alter the forces exerted on neighboring molecules and thus produce dimension changes of the crystal.

Ewing supposes as an example that the outer shell consists of magnets at the corners of a cube, the axes lying along the diagonals of the cube and similar poles pointing inwards. The Weber element has eight magnetic poles at the corners of a cube and is capable of turning as a rigid system about the center. Four of the poles have one polarity and the four opposite poles have the other polarity. If an external magnetic field acts on this system it will tend to cause one of the magnetic axes of the Weber element to line up parallel with the field. If the one pole pertaining to this particular axis attracts the nearest poles of the outer shell more strongly than the other pole repels the poles of the outer shell which are nearest it we would expect a contraction of the molecule in the direction of the magnetic field. Contraction of the whole solid in this direction might then be produced. If on the other hand, the repulsion effect of the Weber element predominates the molecular diameter parallel to the field would elongate and the solid would expand in the direction of the magnetic field. Expansions or contractions transverse to the magnetic field would be produced, depending upon whether the repulsions or attractions of the remaining pairs of poles of the Weber element for the external shell predominated. If we suppose the poles of the external shell are not all of the same strength, or if they are not all similarly situated with respect to the inner element, which need not be pivoted at its center, it is easy to see that either contraction or extension of the molecule (and thus of the entire solid) could be pro-

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[10] Ewing, Phil. Mag. **43**, 493, 1922

duced in different directions with respect to the magnetic field; also the direction of the field with respect to the molecule would be a factor in determining the nature of the dimension change.

It appears, therefore, that the latest model of Ewing's for explaining magnetic induction is adequate with scarcely any modifications for explaining the various magnetostrictive effects in crystals. It is hard to see how a simpler model could take account of the diversity of these effects.[11]

The experiments described above emphasize the importance of structure in relation to magnetostriction, so that one is inclined to consider Maxwell's stresses as playing a comparatively small part in the phenomenon. Theories based entirely upon these stresses have never been satisfactory. Another type of theory[12] has pointed out the reciprocal relations between strain and magnetization, e. g., if the length of an iron bar increases when it is in a magnetic field then a stretching of the same bar will increase its magnetization. This theory applied to the present experiments on iron predicts the possibility of diverse variations in magnetization depending on the direction of the strain with respect to the crystalline axes. Ordinarily iron has been found to show an increase of magnetization when stretched in a weak field and a decrease when stretched in a strong field, the critical field where no change is produced being known as the Villari reversal point. It now appears that this particular kind of Villari reversal is not necessarily characteristic of iron. It is probably a consequence of a certain heterogeneous arrangement of crystals in the iron specimens, and the separate crystals may or may not show this reversal.

A further study of the magnetostriction of different crystals is contemplated, in order to determine more accurately the relation of the effect to the crystal axes.

The writer is indebted to the research laboratory of the General Electric Company for very kindly supplying a number of pieces of silicon-iron alloy with large grains from which the iron disks described above were made.

THE RICE INSTITUTE,
HOUSTON, TEXAS
May 2, 1923

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[11] Since this was written an article by Alpheus W. Smith has appeared (Phys. Rev. **22**, 58, 1923) in which the Ewing model is shown to account for magnetostriction, magnetoresistance, and change of thermoelectromotive force on magnetization—also the effect of strain on these phenomena.

[12] J. J. Thomson, "Applications of Dynamics to Physics and Chemistry," p. 47.